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On September 12, 1997, the Mars Global Surveyor (MGS) spacecraft was successfully inserted into a highly elliptical capture orbit about Mars. To establish the required mapping orbit, the MGS spacecraft must supplement its propulsive capabilities by aerobraking. This paper describes the aerobraking strategy developed for the MGS mission. This description includes the aerobraking constraints imposed on the trajectory design, the approach toward aerobraking trajectory control, and the aerobraking flight profile that resulted from the planning activities that occurred after launch. The initial aerobraking results are contrasted to the planned baseline trajectory.

Additionally, this paper describes the aerobraking progress of the MGS spacecraft made following a three week aerobraking hiatus that occurred in October 1997. This hiatus was initiated in order to provide time to evaluate the viability of continuing aerobraking with newly discovered damage to one of the two spacecraft's solar arrays. The results of the stand down forced a major re-evaluation of the MGS mission and this paper briefly describes the new mission outlook.

INTRODUCTION

The Mars Global Surveyor (MGS) spacecraft was successfully launched on November 7, 1996 aboard a McDonnell Douglas Delta II 7925A launch vehicle from Cape Canaveral Air Station (CCAS) in Florida. The primary objective of the Mars Global Surveyor mission is to conduct a global mapping mission of Mars by performing an extended orbital study of the planet's surface, atmosphere, and gravitational and magnetic fields. Key to the success of this mission is the synergy the instrument complement provides to its scientific investigators when the spacecraft is delivered into its final mapping orbit: a low altitude, near-circular, near-polar orbit that is Sun-synchronous with the dayside equatorial crossing at 2:00 PM local mean solar time. The delivery of the spacecraft to this final mapping orbit and the return of science data from that orbit are fundamental to the success of the mission.

Unlike other interplanetary missions, the MGS spacecraft was launched with a mission delta-V (ΔV) deficit of nearly 1250 m/s. This reduction in the spacecraft propulsive capability was necessary in order to permit the development of a spacecraft design that satisfied the payload capabilities of the Delta II launch vehicle during the Earth-to-Mars ballistic launch opportunities of November 1996. To successfully establish the desired mapping orbit at Mars, the inherent mission ΔV deficit must be overcome by aerobraking[1-5]. Aerobraking is accomplished by lowering the periapsis altitude of the orbit into the upper reaches of the Martian atmosphere and allowing drag forces to reduce the orbital energy. As the orbital energy is reduced, the orbital period of the spacecraft will be reduced. The MGS mission will use aerobraking techniques to reduce the initial capture orbit period about Mars from 45 hours down to the desired mapping orbital period of just less than 2 hours. Because of the mission requirement for a dayside equatorial crossing of 2:00 PM local mean solar time, aerobraking must be completed within four and a half months after arrival at Mars. The 2:00 PM dayside equatorial crossing is achieved by transitioning the local mean solar time of the descending node from 5:45 PM at arrival to the desired 2:00 PM condition. During this four and a half month period, the spacecraft will perform 450 orbits around the planet.

This paper describes the aerobraking strategy developed for the MGS mission. This description includes the aerobraking constraints imposed on the trajectory design, the approach toward aerobraking trajectory control, and the aerobraking flight profile that resulted from the planning activities that occurred after launch. The initial aerobraking results are contrasted to the planned baseline trajectory. Additionally, this paper describes the aerobraking progress of the MGS spacecraft made following a three week aerobraking stand down that occurred in October 1997. This hiatus was initiated in order to provide time to evaluate the viability of continuing aerobraking with newly discovered damage to one of the two spacecraft's solar arrays. The previously undetected damage was attributed to a failure that occurred during the original solar array deployment sequence at launch. The review concluded that it was safe to resume aerobraking albeit at much lower levels of dynamic pressure. The results of the stand-down forced a major re-evaluation of the MGS mission and this paper briefly describes the new mission outlook.

AEROBRAKING STRATEGY AND PLANNING

Aerobraking strategy and planning is a highly interdisciplinary engineering task that has a central focus on the aerobraking trajectory design element. This element is a "tie" point for the mission where various project components are synthesized together. Components which must be integrated into the aerobraking flight profile include the fundamental mission objectives, the programmatic decisions aimed at reducing mission risk, the operating limitations of the spacecraft, as well as the approach toward trajectory control and flight operations implementation.

Aerobraking Sub-Phases

To facilitate the planning process and the flight profile development, the MGS mission has broken aerobraking down into three distinct phase: a walk-in phase, a main phase, and a walk-out phase. During the walk-in phase, the spacecraft will establish initial contact with the atmosphere. This phase continues until dynamic pressure values associated with the main phase are established. During main phase, large scale orbit period reduction will occur as the spacecraft is guided to dynamic pressure limits. Main phase continues until the orbit lifetime of the spacecraft reaches two days. Orbit lifetime is defined as the time it takes the apoapsis altitude of the orbit to decay to an altitude of 300 km. When the orbit lifetime of the spacecraft reaches two days, the aerobraking walk-out phase will begin. During the walk-out phase, the periapsis altitude of the orbit is slowly increased as the two day orbit lifetime of the spacecraft is maintained. Figure 1 illustrates the various aerobraking phases of the MGS mission.

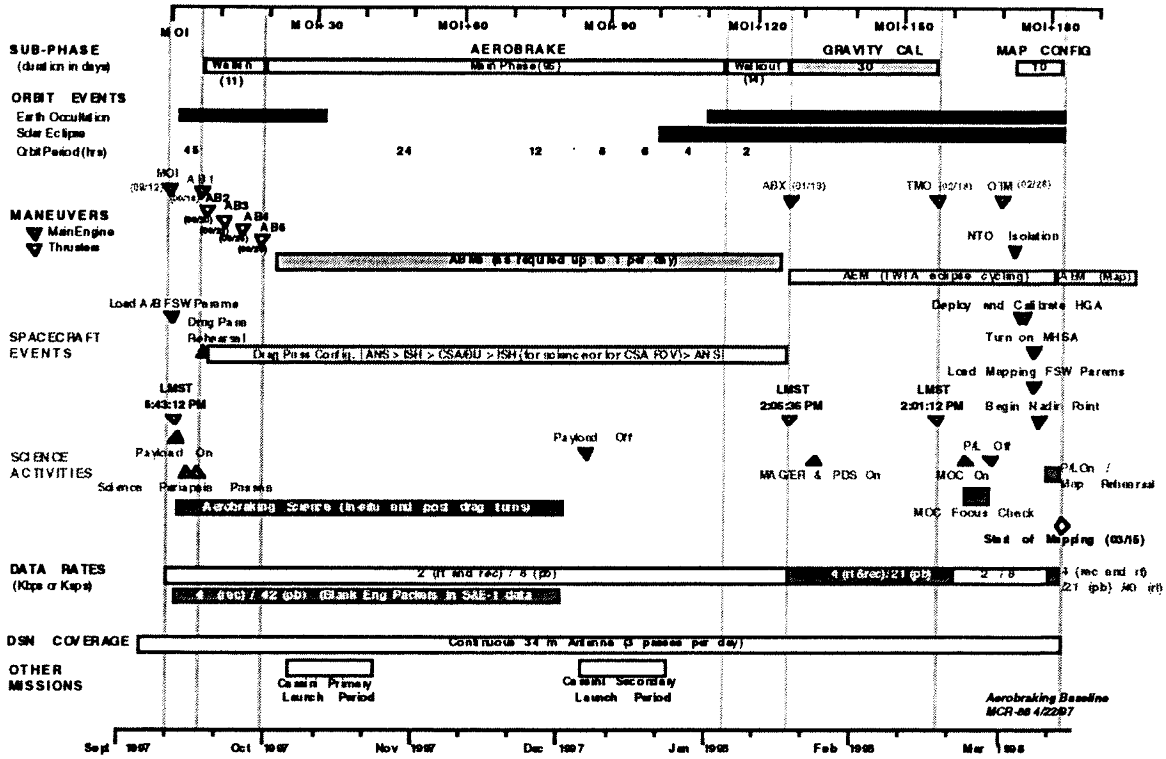

Figure 1 Aerobraking Overview

Aerobraking Requirements and Constraints

The top-level requirement placed on the development of the aerobraking flight profile is a programmatic constraint to maintain the capability to accomodate a total orbit-to-orbit atmospheric density variation of 90%. This “aerobraking density margin” constraint is composed of two distinct parts. The first part is an anticipated intrinsic atmospheric variability (orbit-to-orbit) of 70%. The intrinsic variability of the Martian atmosphere is one of the greatest unknowns the mission faces. That is because the MGS spacecraft must be flown in an altitude ban that separates the lower and upper portions of the Martian atmosphere (i.e. an atmospheric boundary layer). In this region, the environment and the associated physical processes that occur are not well understood yet. The second component of the “atmospheric density margin” is an uncertainty associated with navigating the spacecraft about Mars. This 20% navigation uncertainty is due to unanticipated periapsis altitude variations caused by the Martian gravity field.

This “aerobraking density margin” constraint is applied against the most sensitive spacecraft components. Prior to launch, it was anticipated that this “atmospheric density margin” constraint would be driven by the thermal limitations of the vehicle and would be expressed in terms of a free stream heating rate requirement. In addition to thermal limitations of the spacecraft, power limits are a concern during those period in time when the spacecraft must stay on batteries for an extended duration. The spacecraft is required to maintain a battery state of charge (SOC) greater than 40% and an energy balance greater than 40 W-Hrs. This condition is most threatened when the spacecraft enters periods of solar eclipse just prior to a drag pass and the off-sun durations approach one hour.

To achieve the mission requirement for a 2:00 PM Sun-synchronous mapping orbit, the orbit period reduction associated with aerobraking must proceed in a timely manner. When the 2:00 PM mapping orbit requirement is combined with the "atmospheric density margin" constraint, the result is a trajectory design space that is bounded by fundamental mission requirements on one side and spacecraft operating limitations on the other. Thus, the spacecraft must be flown at altitudes, or more correctly dynamic pressure levels, sufficient to produce the desired orbital decay rates, but not so low as to damage or destroy key spacecraft components in the presence of the anticipated atmospheric variation. To successfully establish the desired mapping orbit, the MGS spacecraft must aerobrake from its initial capture orbit apoapsis altitude of 54000 km down to an apoapsis altitude of 450 km; or equivalnetly, an initial capture orbit period of 45 hours down to an orbit period of 1.9 hours. Once the spacecraft reaches an apoapsis altitude of 450 km, the spacecraft propulsive capability is sufficient to establish the final mapping orbit.

Aerobraking Trajectory Control

To support aerobraking operations, near continuous tracking coverage of the spacecraft has been scheduled with the Deep Space Network (DSN). This coverage permits a rapid assessment of the spacecraft health following each drag pass and supports the navigation orbit determination process. The post drag state of the spacecraft as well as the orbit determination results are important inputs into the aerobraking trajectory control process. A third input into the trajectory control process consists of atmospheric data collected onboard the MGS spacecraft via the science instrument payload and engineering instrumentation, as well as Earth ground based microwave (temperature) measurements of Mars. Early in aerobraking, the atmospheric data included images of Mars taken from the Hubble Space Telescope and meteorology data collected by Mars Pathfinder Lander. The atmospheric data is then combined in a synthesis process in order to characterize the current state of the Martian atmosphere. Of particular concern are atmospheric measurements that indicate the onset of dust storms on the planet. On the onset of a dust storm, the atmospheric density could more than double in a forty-eight hour time period. To mitigate the risk of damage to the MGS spacecraft due to a rapid increase in the atmospheric density associated with a dust storm, the altitude of the spacecraft can then be raised through the trajectory control process. It should be noted that the dust storm threat to the MGS spacecraft is of particular concern since the aerobraking operations occur during the height of the dust storm season on Mars. To support aerobraking operations, it was anticipated that data collection from the MGS the science instrument payload would continue until a ten hour orbit period was reached. At the ten hour mark, this data would no longer be available because of spacecraft telemetry rate and power margins.

Control of the flight path of the spacecraft during aerobraking is achieved by performing small propulsive maneuvers at apoapsis. These small maneuvers are called aerobraking trim maneuvers (ABMs) and are used to maintain the spacecraft in a dynamic pressure "corridor." Guiding the vehicle to a dynamic pressure corridor decouples the actual trajectory from any particular atmospheric model. In other words, the guidance strategy is independent of the periapsis altitude over the planet. Of course, assumptions regarding the character (or scale height) of the atmospheric model must be consistent with the observed atmospheric characteristics during the actual flight of the vehicle. Otherwise, the actual dynamic pressure "settings" will, by necessity, need to be adjusted in order to achieve the desired orbit period reduction per pass. The dynamic pressure parameter which is related to the force the vehicle experiences as it flies through the atmosphere is easily deduced during the navigation orbit determination process and from accelerometer measurements obtained during an atmospheric drag pass.

Rather than design maneuvers on an orbit-by-orbit basis, the trajectory control process at any one time makes use of discrete maneuver sizes or ΔV magnitudes which are a function of the current orbital period and two maneuver directions (quaternions) which are a function of the current argument of periapsis. The maneuver sizes and directions together form an ABM specification. Once a week, the trajectory control parameters are reviewed and updated if necessary. The ABM maneuver magnitudes are selected in order to provide appropriate control authority over the dynamic pressure corridor. The minimum ABM magnitude that may be employed in the trajectory control process is equal to 0.05 m/s. This minimum maneuver size is principally due to the maneuver execution errors associated with the spacecraft's attitude control subsystem. In addition to the magnitude constraint, the ABM maneuvers must satisfy a payload sun avoidance constraint. This constraint is violated if the burn direction of any maneuver causes the science payload to come within 43 degrees of the sun. The ABM maneuver frequency is generally limited to one maneuver every 24 hours. This limit was originally selected in order to support battery recharge requirements once the spacecraft entered periods of eclipse.

Post-Launch Revisions to the Baseline Aerobraking Planning

Following launch, the aerobraking strategy for the MGS mission was reviewed and three significant revisions were incorporated into the baseline planning. The first revision was aimed at accommodating a failure that occurred during the solar array deployment sequence: the inboard hinge line of one of the two spacecraft's solar arrays failed to properly latch[6]. This required modifications to the original spacecraft aerobraking configuration. The new spacecraft aerobraking configuration was devised in order to ensure that aerobraking could safely proceed with the solar panel unlatched. As the new aerobraking configuration was being developed, its was thought that the "atmospheric density margin" constraint discussed previously may have to be applied against the mechanical holding torque limitations of the solar array gimbal. This would be expressed as a constraint on the trajectory design in terms of dynamic pressure. However, additional testing of the gimbal holding torque showed that thermal limitations of the spacecraft would still be the most demanding constraint. Figure 2 shows the revised MGS spacecraft aerobraking configuration.

The second revision to the aerobraking strategy was aimed at providing additional days of "aerobraking margin" against the 2:00 PM mapping orbit constraint. This was achieved by reducing the capture orbit period from 48 to 45 hours by increasing the maneuver magnitude of the Mars orbit insertion (MOI) maneuver; essentially trading time against propellant. Additionally, the initiation of aerobraking was accelerated by four days by deleting two orbits of activities in the capture orbit.

The third revision incorporated a measure of dynamic pressure shaping into the trajectory design. This strategy was incorporated into the flight profile in order to increase the initial "atmospheric density margin" to values greater than the 90% requirement. This was accomplished by employing a dynamic pressure control approach that changed in steps as a function of orbital period.

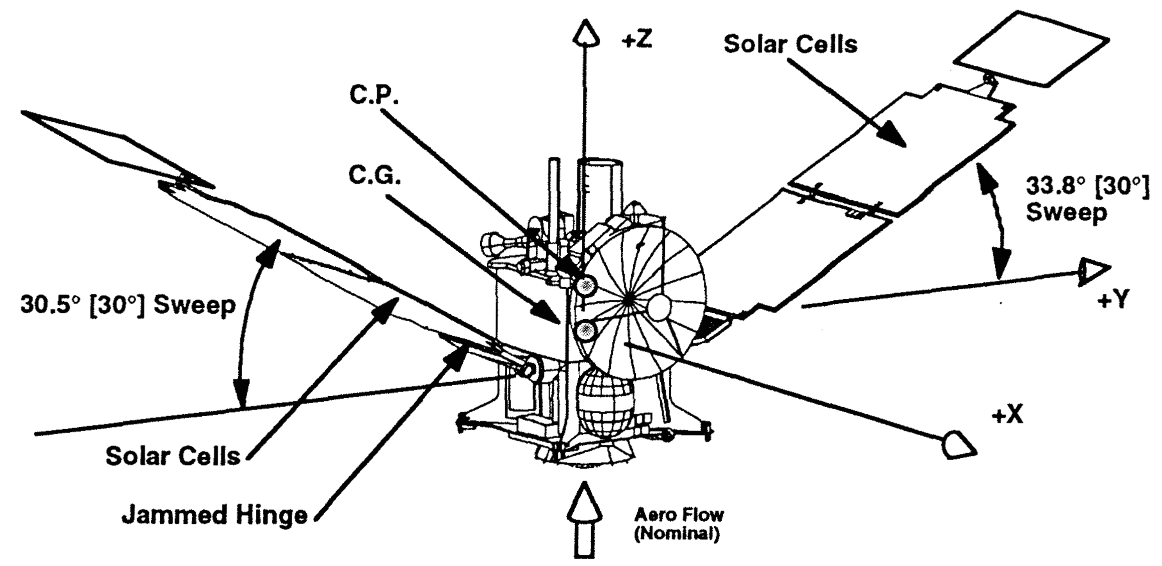

Figure 2 Revised MGS Spacecraft Aerobraking Configuration

Baseline Aerobraking Flight Profile (September 1997): "Aerobraking Flight Profile to the 2:00 PM Mapping Orbit"

The aerobraking flight profile developed during the aerobraking planning process is described below. The baseline trajectory was developed using the Mars-GRAM Atmospheric Model[7-8] and was designed to accommodate the various aerobraking requirements and constraints discussed previously. The aerobraking flight profile also forms the basic guidance framework for the trajectory control process.

Aerobraking is initiated from the original capture orbit that results from the Mars orbit insertion maneuver. The nominal capture orbit was planned to have an orbit period of 45 hours and a periapsis altitude of 250 km. First contact of the spacecraft with the atmosphere begins during the aerobraking walk-in phase. This first maneuver in the walk-in phase lowers the altitude of the spacecraft to 150 km. This altitude was selected because it was anticipated that safety of the vehicle would not be threatened by the atmospheric drag forces at that altitude for virtually any atmospheric condition. The next altitude step in the walk-in sequence is based on the usage of an atmospheric density estimate determined by navigation from the 150 km altitude coupled with a limiting "critical" density value derived from spacecraft free stream heating rate requirements. The computation of the critical density value takes into account the programmatic requirement for a 90% atmospheric density margin. The actual density estimate from navigation coupled with the limiting "critical" density value and the usage of a conservative density scale height of 3.5 km result in the next maximum altitude step in the walk-sequence.

The first three maneuvers of the walk-in sequence are performed at apoapases one orbit apart from each other (refer to Figure 1). After the third walk-in maneuver is performed, subsequent walk-in maneuvers will be performed every other orbit until main phase is established. The walk-in phase was designed to take just over ten days and required five maneuvers. The walk-in phase is terminated when main phase dynamic pressure values are established.

Once main phase is established, large scale orbit period reduction begins. During this period in time, the orbit reaches its maximum orbital decay rates. Figure 3 illustrates the orbit period reduction as a function of date. To establish the proper mapping orbit conditions, aerobraking must reduce the capture orbit period to an orbit period less than 2 hours by the time the descending node reaches the 2:00 PM local mean solar time

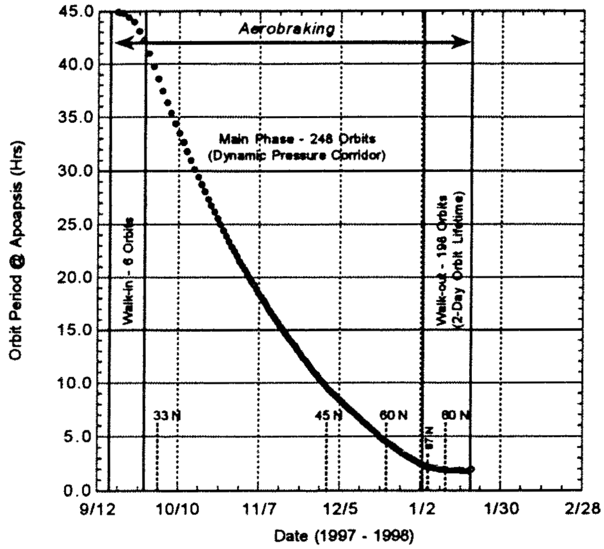

Figure 3 Orbit Period Reduction
(Baseline Aerobraking Flight Profile - September 1997)

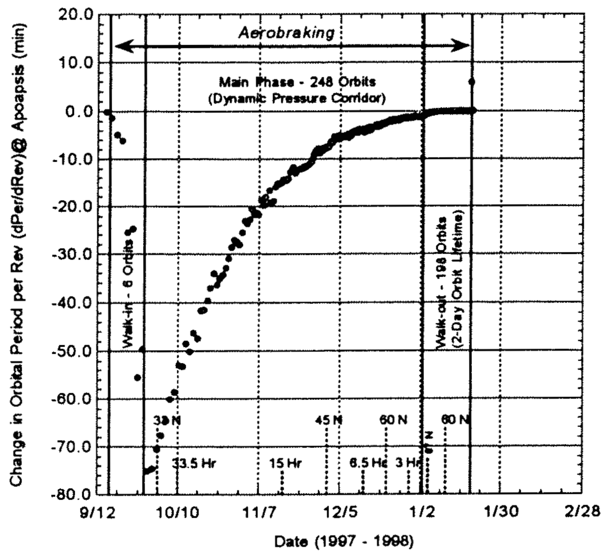

Figure 4 Change in Orbit Period Per Orbit
(Baseline Aerobraking Flight Profile - September 1997)

orientation -- roughly a four and a half month time period. Thus, the orbit period reduction achieved as a result of aerobraking must proceed at a pace very close to that shown in Figure 3. Because of the linkage of the orbit period reduction to a time requirement imposed by the phasing of the descending node, Figure 3 is often referred to as the "glide slope" of the aerobraking trajectory. The change in orbital period per orbit associated with the "glide slope" is shown in Figure 4. Note the large scale orbit period reduction that occurs early in aerobraking - an orbit period reduction per orbit greater than 60 minutes.

Figure 5 shows the progression of the local mean solar during aerobraking. The flattening of this curve near the end of the main phase is indicative of the sun-synchronous orbit condition, a mission requirement. Additionally, it should be noted that the baseline trajectory reaches 2:15 PM at the time of planned aerobraking termination. This "15 minutes" provides a measure of "aerobraking margin" against the 2:00 PM condition in the event aerobraking becomes delayed

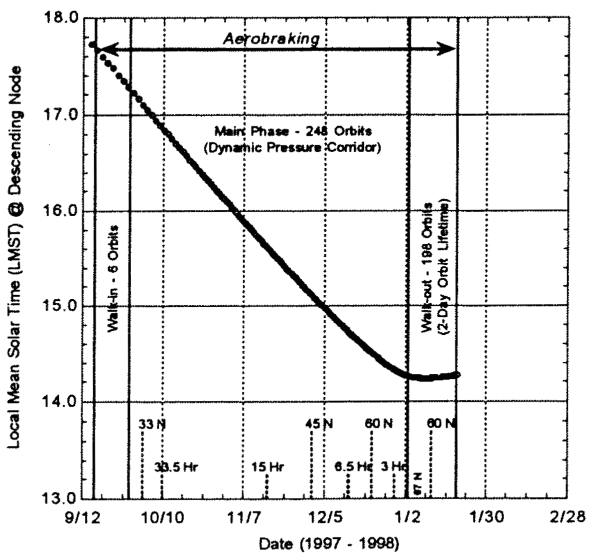

Figure 5 Local Mean Solar Time
(Baseline Aerobraking Flight Profile - September 1997)

As a result of the northerly approach over the planet used for the MOI maneuver, the periapsis of the capture orbit is at 32 degrees North latitude at the start of aerobraking. Due to the influence of the Martian gravity field, periapsis begins a slow track northward over the planet. Figure 6 shows the latitude of periapsis as a function of date. To maintain the desired dynamic pressure conditions, the periapsis alitude is gradually lowered along this northward track. This is necessary because of the expected drop off of the atmosphere as the vehicle enters the northern polar cap of the planet -- an area generally considered to begin at approxmately 60 degress North latitude.

In addition to the large scale changes of the orbit geometry during main phase, the spacecraft experiences maximum heating rates and maximum dynamic pressures. During

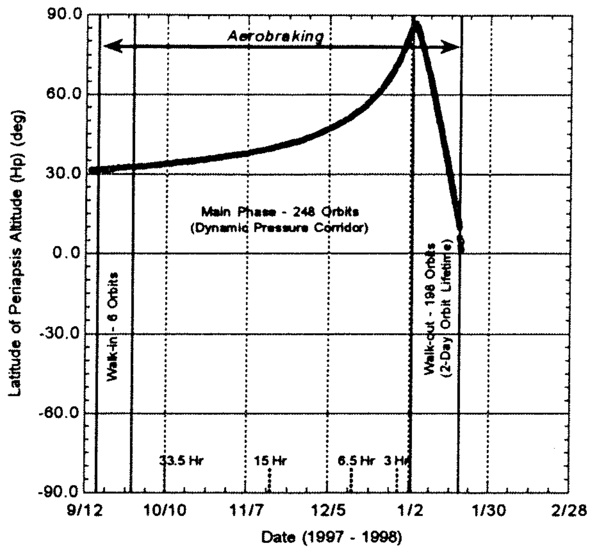

Figure 6 Latitude of Periapsis
(Baseline Aerobraking Flight Profile - September 1997)

this time period, the spacecraft is guided between dynamic pressure limits in order to control the orbit period reduction progress. Figure 7 shows a "stepped" dynamic pressure control process. This figure also shows a line that demarcates the 90% atmospheric density variation limit. If during aerobraking, the spacecraft experiences dynamic pressure values greater than this limit line, the periapsis altitude of the orbit must be raised immediately in order to re-establish the 90% atmospheric density capability. A small raise in the periapsis altitude will drop the dynamic pressure the vehicle experiences on the next drag pass. It should be noted that the 90% atmospheric density variation limit was derived from free stream heating rate requirements developed from the thermal limitations of the vehicle and were "mapped" into the dynamic pressure space to support the trajectory control process.

The usage of steps in the dynamic pressure control process provides a means to shape the trajectory around the variable free stream heating rate limits. The free stream heating rate limits are not constant because they are dependent upon the amount of time the spacecraft spends in the atmosphere on a given orbit, called the drag pass duration, and other associated orbit geometry. Drag pass durations vary anywhere from 350 seconds in early main phase up to 1000 seconds during the walk-out. This schedule of "stepped" dynamic pressure values results in an overall main phase average dynamic pressure of 0.59 N/m2 per drag pass and produces the orbit period reduction shown in Figure 3.

The dynamic pressure corridor is maintained by performing small ABMs. In an attempt to minimize the ABM maneuver frequency while at the same time maintain the appropriate orbital decay rate, the lower and upper limits of the dynamic pressure corridor are separated by a value of 0.1 N/m2. As the orbital period decreases, the frequency of the ABM maneuvers increase.

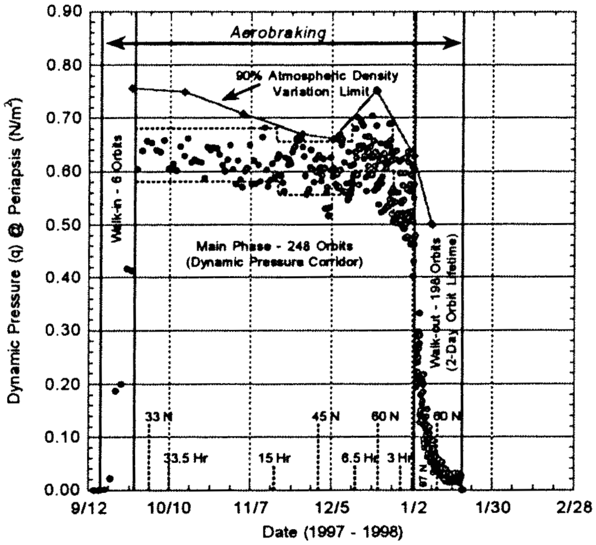

Figure 7 Dynamic Pressure at Periapsis
(Baseline Aerobraking Flight Profile - September 1997)

Main phase continues until the orbit lifetime of the spacecraft reaches two days. This typically occurs at about the time the orbit period reaches the 2.4 hour mark -- an equivalent apoapsis altitude of 1800 km.

During walk-out, orbit period reduction continues as the orbit decay rate slows. Additionally, the spacecraft heating rates and dynamic pressures are reduced by an order of magnitude as periapsis crosses the North Pole and begins to drift south. As periapsis drifts southward over the planet, the periapsis altitude must be continually raised to maintain the two day orbit lifetime. This is accomplished through the execution of daily ABM maneuvers. Once the 450 km apoapsis altitude is reached, the periapsis altiude of the orbit is raised and aerobraking is terminated. The aerobraking termination maneuver requires nearly 60 m/s and initiates a transition phase aimed at establishing the final mapping orbit.

Aerobraking Operations - Initial Aerobraking Results

After a ten month interplanetary transit[9], the spacecraft was successfully inserted into the desired elliptical capture orbit about Mars on September 12, 1997. The MOI maneuver used 973 m/s and exhausted 77% of the remaining propulsive capability of the spacecraft. The initial capture orbit had an orbital period of 45 hours and a periapsis altitude of 263 km. To mark the orbital progress of the spacecraft around the planet, each orbit is numbered sequentially with each periapsis used to demarcate the start of each new orbit.

Aerobraking operations commenced three orbits later with the first walk-in maneuver lowering periapsis altitude to 150 km. Five more walk-in maneuvers were performed using the basic walk-in methodology described above. On October 2, 1997 (orbit number 12), the aerobraking main phase was established at an altitude of 110.5 km with an intial dynamic pressure value of 0.53 N/m2. The six walk-in maneuvers used a total ΔV of 5.99 m/s.

Aerobraking operations continued according to plan until October 7, 1997 (orbit number 15). At the periapsis drag pass of orbit number 15, the spacecraft encountered a perispsis dynamic pressure value of 0.90 Nm2. Because this value reduced the atmospheric density margin to values less than 90%, periapsis altitude was immediately raised to reduce the dynamic pressure on the next drag pass. Figure 8 shows the actual dynamic pressure history as well as the associated trajectory control maneuvers (ABMs).

Following the 0.9 N/m2 drag pass, newly observed inconsistencies in the spacecraft telemetry data emerged. Spacecraft health assessments performed during the next three orbits of aerobraking tentatively concluded that the solar array failure mode postulated after launch may not fully explain the original deployment anomaly and the state of the solar array. To better understand the viability of continuing aerobraking with the damaged solar array, aerobraking operations were temporarily suspended on October 12, 1997 (orbit number 18) and the periapsis altitude of the orbit was raised to 172 km. The consequence of this action meant that the 2:00 PM requirement imposed on the mapping orbit could no longer be achieved in the specified time frame.

Figure 9 shows the orbit period reduction achieved during the first three weeks of aerobraking. When the periapsis altitude of the orbit was raised to 172 km on October 12, 1997, the orbit period had been reduced to a value slightly less than 35 hours (i.e. more than ten hours of orbit period reduction had occurred since initial capture about Mars).

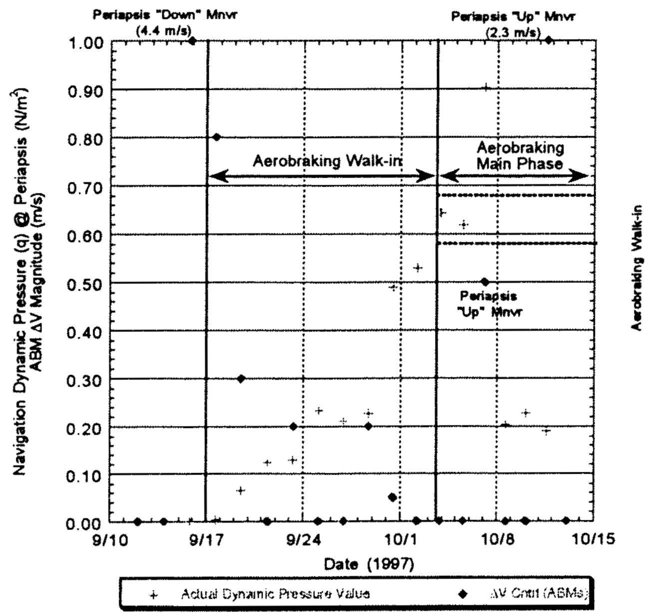

Figure 8 Actual Dynamic Pressure at Periapsis
(September - October 1997)

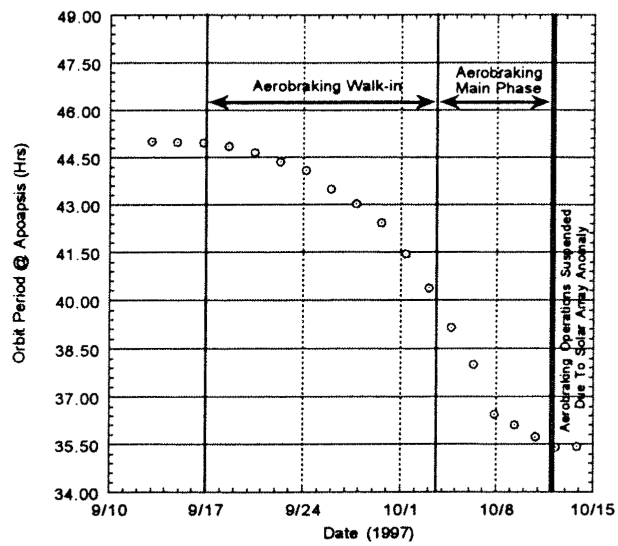

Figure 9 Actual Orbit Period Reduction
(September - October 1997)

AEROBRAKING RESTART PLAN

In parallel to the review of the spacecraft health status, an intensive mission replanning effort was begun. Initial results of the mission replanning effort concluded that due to the mapping orbit science requirements of the individual instruments, the nature of the spacecraft design, and spacecraft operability issues, the highly elliptical orbits that could be achieved with the remaining total spacecraft propulsive capability (293 m/s) were undesireable in terms of achieveing the primary aims of the MGS mission. The best mapping orbits for the MGS spacecraft were still those orbits that could be characterized as low altitude and near-circular. Without aerobraking capability, the MGS spacecraft would not be able to reach orbits that supported the science data return necessary to complete the primary global mapping mission.

Revised Aerobraking Flight Profile (November 1997): "Aerobraking Flight Profile to Solar Conjunction"

After three weeks of intensive review of the spacecraft telemetry data and ground testing of the flight hardware spares, it was concluded that it was safe to resume aerobraking at dynamic pressure levels averaging 0.2 N/m^2. This new dynamic pressure limitation was immediately incorporated into the mission replanning activities.

Holding paramount the primary objectives of the MGS mission, the mission timelines were revised based on aerobraking at the newer lower levels. The result was the development of a new mission that requires two distinct periods of aerobraking separated by an aerobraking hiatus that would last for several months in an intermediate orbit designated the "science phasing orbit." The first period of aerobraking would begin immediately and would continue until the orbit period associated with the intermediate science phasing orbit was reached. For various reasons, an 11.6 hour orbit period was selected for the science phasing orbit. Pragmatically this orbit must be reached by April 22, 1998 -- one week prior to the start of solar conjunction with Mars. Aerobraking must be terminated prior to solar conjunction because of the communications degradation and the actual loss of communications that occurs with the spacecraft during this time period. (The MGS mission has defined solar conjunction as the time period from May 1, 1998 through May 24, 1998.) To satisfy the mapping orbit requirement for a 2:00 PM dayside equatorial crossing, the second period of aerobraking will be initiated in time to transition the ascending node of the orbit to the 2:00 PM condition. This second period of aerobraking will begin in September 1998 and last until early February 1999 and require nearly 700 orbits around the planet. Figure 10 shows the revised MGS mission timeline.

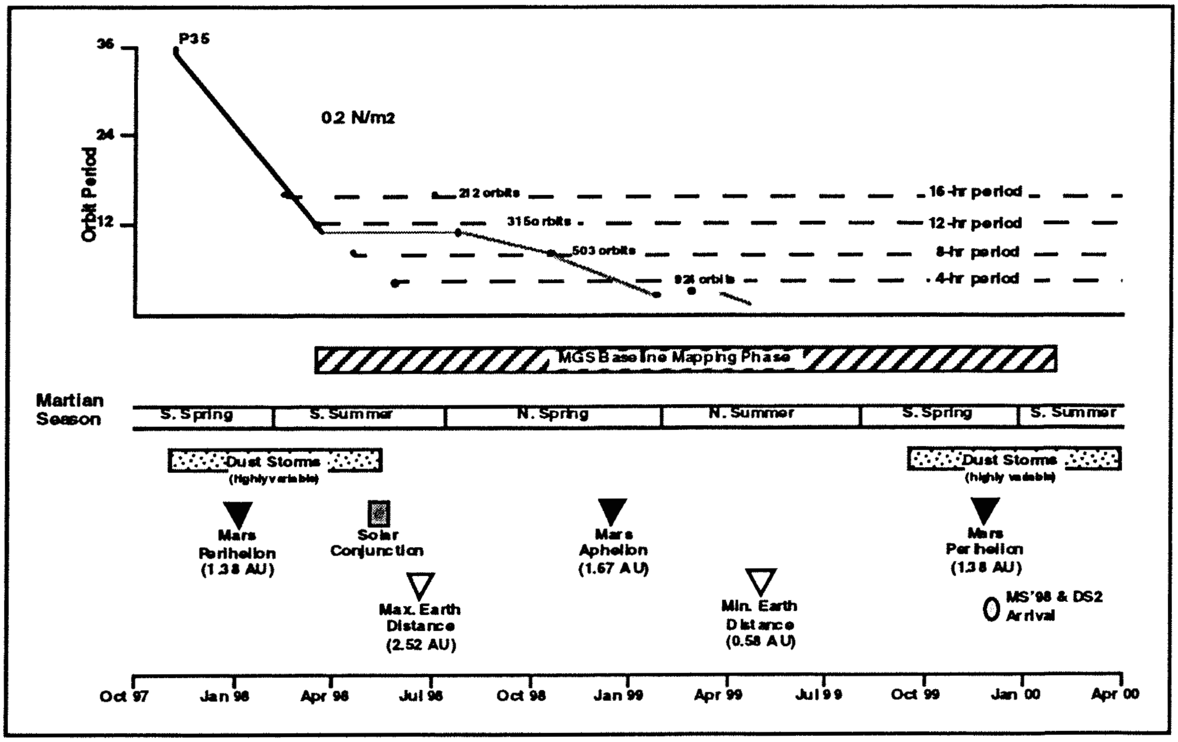

Figure 10 Revised MGS Mission Timeline

With the new dynamic pressure limitations imposed on the aerobraking trajectory, the baseline aerobraking flight profile was updated. Figure 11 shows the orbit period reduction as a function of date during the current phase of aerobraking and Figure 12 shows the corresponding change in orbit period per orbit. Note the sharp contrast in these values compared to those in Figures 3 and 4. The dynamic pressure control used in the development of this new profile is shown in Figure 13.

Aerobraking Results To Date - January 1998

Aerobraking was re-initiated on November 7, 1997 (orbit number 36) with an initial periapsis altitude lowering to 135 km. A walk-in scheme similar to the original walk-in scheme was used and the new aerobraking main phase was established on November 15, 1997 (orbit number 42) at a periapsis altitude of 120.5 km with a dynamic pressure of

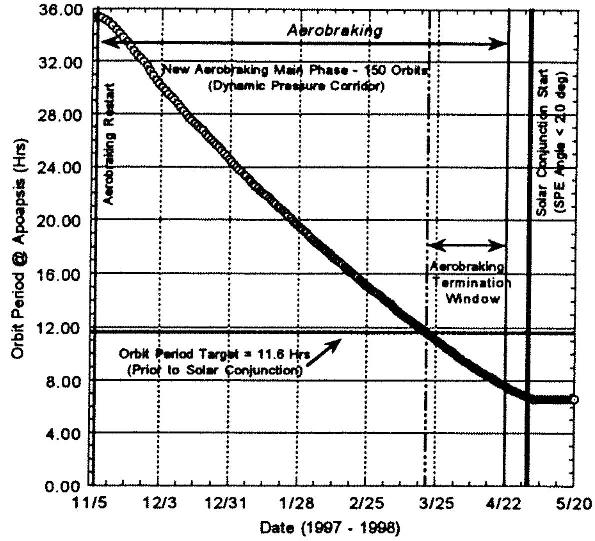

Figure 11 Orbit Period Reduction
(Revised Aerobraking Baseline Trajectory - November 1997)

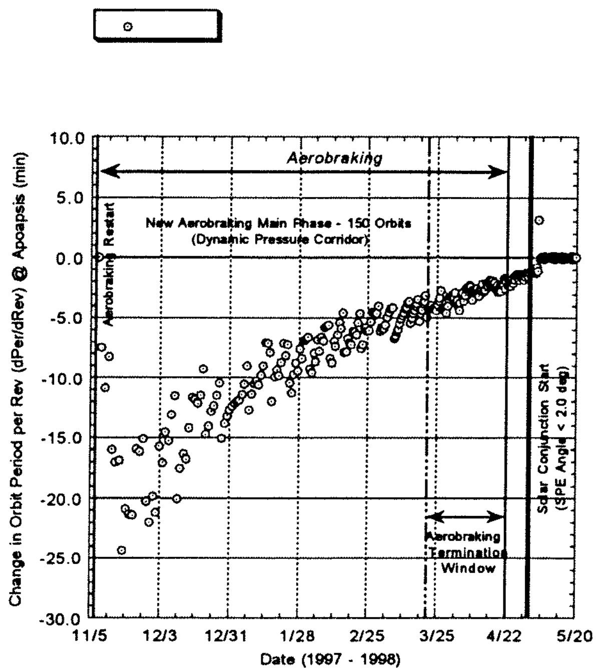

Figure 12 Change in Orbit Period Per Orbit
(Revised Aerobraking Baseline Trajectory - November 1997)

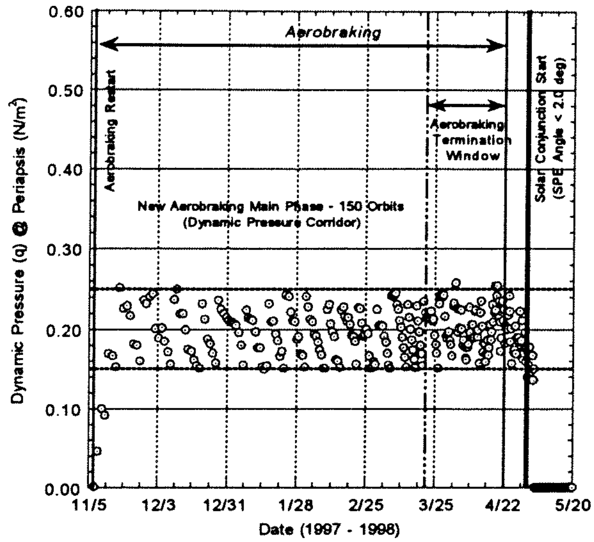

Figure 13 Dynamic Pressure at Periapsis
(Revised Aerobraking Baseline Trajectory - November 1997)

0.26 N/m2. Figure 14 shows the actual dynamic pressure history versus date as well as the associated ABMs. In addition Figure 13, shows a 3-orbit running mean in the dynamic pressure. The 3-orbit running mean in dynamic pressure is a simple procedure that is used

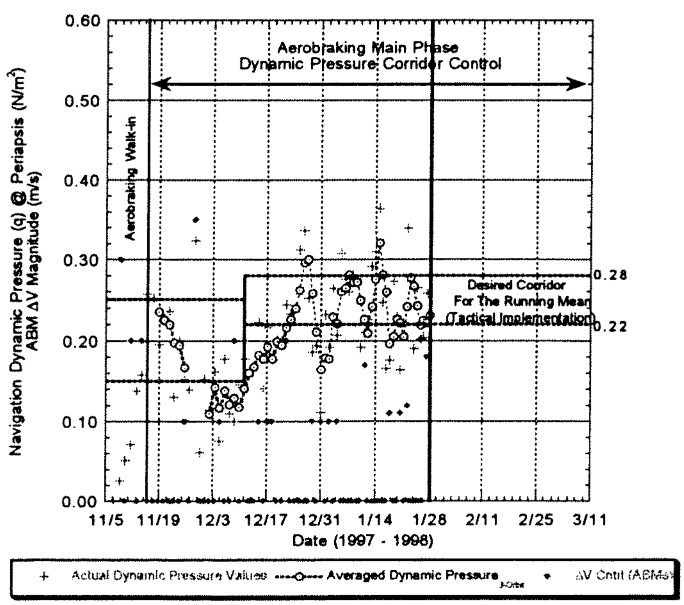

Figure 14 Actual Dynamic Pressure at Periapsis
(November 1997 - January 1998)

to support the trajectory control process by smoothing the intrinsic orbit-to-orbit atmospheric variability.

As before, the establishment of the aerobraking main phase went according to plan. However, on November 23, 1997 (orbit number 50), the spacecraft encountered a dynamic pressure value of 0.32 N/m2 and atmospheric measurements indicated the presence of a large disturbance in the atmosphere. In response, the periapsis altitude of the spacecraft was raised to an altitude of 130 km. The resultant atmospheric disturbance evolved into a regional dust storm centered over the Nocachis of the planet region (Latitude = X South, Longitude = 0 East). The signature of the storm is clearly evident when the dynamic pressure values are normalized to a common altitude. This signature is shown in Figure 15. Figure 14 shows the corresponding drop in the averaged dynamic pressures to values near 0.12 N/m2 due to the ABM maneuver performed to raise periapsis altitude.

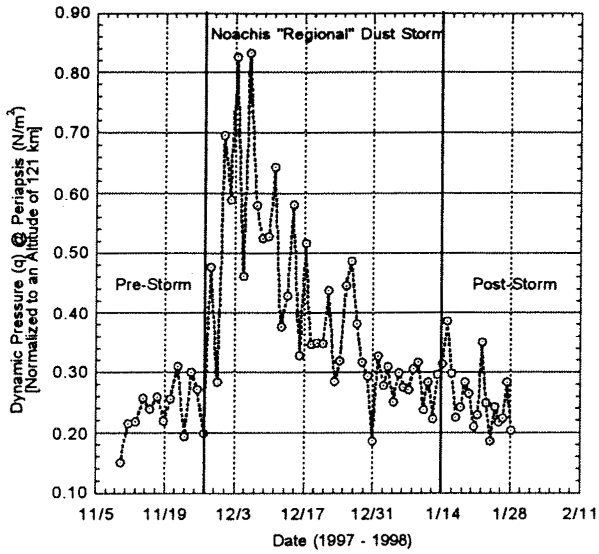

Figure 15 Actual Dynamic Pressure - Normalized To An Altitude of 121 km (November 1997 - January 1998)

Figure 16 shows the orbit period reduction progress made since the aerobraking restart in November 1997. The actual results are shown contrasted against the "glide slope" of the revised baseline trajectory. Deviations from the revised baseline trajectory began when the periapsis altitude was raised in response to the dust storm threat and continued until the difference between the revised baseline and the actual trajectory reached a maximum value of 97 minutes. With the dust storm waning, aerobraking resumed at dynamic pressures averaging just under 0.2 N/m2. After several weeks of aerobraking near the dynamic pressure level of 0.2 N/m2, it was concluded that in order to parallel the "glide slope" of Figure 11, the actual values of the periapsis dynamic pressure would have to be increased by fifteen to twenty percent. In other words, the character of the actual Martian atmosphere was not producing the desired orbital decay rates for the anticipated range of dynamic pressure. Hence, as Figure 14 shows, the average periapsis dynamic pressure values were raised to values over 0.2 N/m2. As a result, the gap between the actual orbit period reduction achieved to date and the revised baseline trajectory began to close. As of February 4, 1998, the difference between the actual trajectory and the baseline trajectory has been reduced to 12.4 minutes. The ability to guide the actual trajectory along a prescribed "path" will be critical for the second period of MGS aerobraking because of the aerobraking timing limitations imposed by the 2:00 PM mapping orbit geometry.

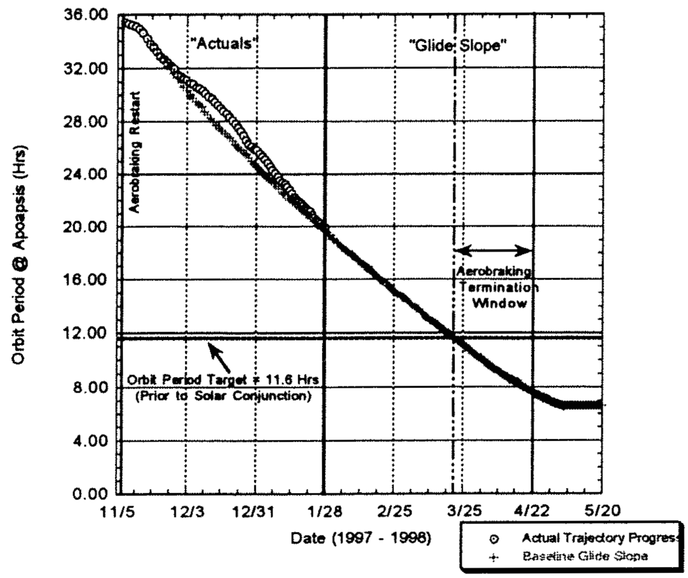

Figure 16 Actual Orbit Period Reduction
(November 1997 - January 1998)

CONCLUSIONS - REVISED MGS MISSION

As of February 5, 1998, the MGS spacecraft continues to aerobrake with dynamic pressure levels averaging 0.23 N/m2. Using aerobraking, the orbit period of the MGS spacecraft has now been reduced to 18.4 hours (i.e. more than 26 hours of orbit period reduction have occurred since initial capture at Mars). The periapsis altitude of the orbit of the MGS spacecraft is near 121 km and is moving slowly northward from its current location of 48 degrees North latitude. The spacecraft health is characterized as good and progress is being made toward achieving the primary aims of the MGS mission.

The MGS mission replanning activities are continuing with the development of the detailed planning for the intermediate science phasing orbit and the second period of aerobraking well underway. With the development of the new mission baseline, the MGS spacecraft must now aerobrake for close to a year and complete nearly 1200 aerobraking orbits before establishing its final mapping orbit around Mars. In addition to the development of the new mission baseline, the mission replanning activities are also characterizing alternative mapping orbits for the MGS spacecraft in the event further anomalies occur and aerobraking must be permanently terminated.

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